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PRINT FIG. Fig. 1

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NASA CASE NO. LEW-16,257-1

PULSE-ECHO ULTRASONIC IMAGING METHOD FOR ELIMINATING SAMPLE THICKNESS VARIATION EFFECTS

ORIGIN OF THE INVENTION

The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

Field of the Invention

The invention relates to ultrasonic evaluation of material properties. More particularly, the invention relates to nondestructive ultrasonic evaluation of materials by measuring velocity using a single transducer pulse-echo immersion system, automatic scanning and digital imaging, which provides a video image of the sample in color or grey scale which is a map of a material property such as porosity fraction.

Background of the Disclosure

Nondestructive evaluation applicable to evaluating properties of materials such as ceramics, metals, plastics and various composites are known to those skilled in the art and include x-radiography, ultrasound or ultrasonic evaluation, and thermal methods. These methods provide an efficient, quasi-quantitative measure of material homogeneity, but often lack the precision necessary for microstructure evaluation of high-performance materials, such as high temperature oxidation resistant ceramics and the like. The development and use of materials for high-performance applications requires detailed, quantitative knowledge of microstructural and compositional variability for defining acceptable levels of variability and for rejecting those materials and processes that yield sample-to-sample and within-sample variations likely to result in unacceptable property e.g., strength, thermal conductivity, oxidation resistance, resistance to spalling, etc.) variations. Such variability must be precisely characterized either directly in terms of property measurement or indirectly through microstructural characterization where microstructure-property relations have been previously established.

Repeated, uniformly spaced ultrasonic contact measurements have been successful for quantifying and mapping inhomogeneity in various ceramics (e.g., SiC, Al_2O_3, $YBa_2Cu_3O_7$ and Si_3N_4) and metals in terms of ultrasonic material properties such as reflection coefficient, velocity and attenuation coefficient as mentioned, for example, by Roth, et. al. in *Quantitative Mapping of Pore Fraction Variations in Silicon Nitride Using an Ultrasonic Contact Scan Technique*, NASA TP 3377 (1993). This publication describes quantitatively characterizing material (e.g., Si_3N_4) microstructure in terms of actual ultrasonic wave parameters. The wave parameters include reflection coefficient, attenuation coefficient and velocity. A post-scan interactive data display system is used for comparing ultrasonic properties at different locations within samples and viewing the resultant ultrasonic images. Further refinement of this process is disclosed by Roth, et. al. in *PSIDD: A Post-Scan Interactive Data Display System for Ultrasonic Scans*, NASA TM-4545 (1993). This process relates to contact scans and does not disclose how to account for thickness vatiations in the sample being measured. Piche discloses a single transducer immersion method for evaluating plastic using a technique in which 16 scan points are pulsed for the sample and the results evaluated using regression analysis [L. Piche, *Ultrasonic Velocity Measurement for the Determination of Density in Polyethylene*, Polymer Eng. &. Sci.,v. 24, n. 17, p. 1358-58 (December, 1984)]. This method does not relate to forming an image of the sample property, nor does it provide an experimental technique that automatically accounts for nonlevelness and thickness variation during a scan procedure required to form an image. Consequently, a need still exists for a method which will permit ultrasonic material evaluation that will account for nonlevelness and thickness variations in the material, require only a single transducer, eliminate problems associated with physical contact between the transducer and sample or buffer rod, and display, on a video screen in gray scale or color, an image of the scanned material which is a map of an internal structural property of the material, such as porosity fraction.

SUMMARY OF THE INVENTION

The invention relates to a method for nondestructive ultrasonic evaluation of materials by measuring velocity using a pulse-echo immersion system with automatic scanning, echo cross-correlation and digital imaging to obtain a grey scale or color image of the sample. The velocity values obtained for each scan point are scaled on a grey or color scale and displayed on a video screen which shows a material property, such as porosity fraction. Prior to the automatic scanning, nonlevelness in the set-up and sample thickness variation effects are accounted for and eliminated by insuring that the echoes at each scan point are first gated and input into a scan parameter file in a computer, so that during the subsequent automatic scanning each received echo is centered in the time window set for it. While it is possible, but not practical to do a manual prescan at each and every scan point needed for a two dimensional video image of the material property being evaluated, many sample thickness variations are in the form of a uniform thickness variation from one edge to another. In this case of uniform thickness variations from one edge to another, preliminary scans are performed along a single line in both the x- and y- directions of the sample to provide slant correction factors. The slant correction factors are input into the scan parameter file so that any wedge-shape variations are taken into account during the automatic scanning for the material evaluation, to insure that each echo received during the automatic scanning is centered within the time window. A single transducer is used in a preferred embodiment of the invention.

In the immersion method of the invention, the material to be evaluated is surrounded by a liquid and positioned over an accoustic reflector which is also immersed in the liquid. An ultrasonic wave of a known frequency is transmitted through the liquid and four separate echoes are recorded and evaluated at each scan point. Each echo is received as an analog waveform which is digitized and stored in a computer. The echoes received, digitized and stored during the sample evaluation scans are the first two succesive echoes reflected off the back surface of the sample, the first echo reflected off the front surface of the accoustic reflector in which the received wave has passed through the sample, and the forth is the first echo reflected off the front surface of the reflector with the sample not present, so that the received wave does not pass through the sample. This means that at least two separate scans must be made, with and without the sample present between the transducer and reflector. However, as a practical matter it is difficult from both a hardware and software perspective to accomplish this in just two scans and obtain maximum time resolution and thus maximum accuracy. Consequently three or four separate scans are performed, with three being faster and four being more accurate. The choice is left to the discretion of the practitioner.

In the embodiment in which four separate scans are performed during the sample evaluation, the ultrasonic wave goes through both the liquid and the material during the first three scans. For the forth scan the material sample is removed so that the transmitted wave is reflected off the front surface of the reflector without going through the material. Although the order is not important, it is convenient to receive the first echo reflected off the back surface of the material during the first scan and the second successive echo reflected off the back surface of the sample during the second scan. During the third scan in which the transmitted wave goes through both the immersion liquid and the material sample, the first echo reflected off the front surface of the reflector is received. The first echo reflected off the front reflector surface is received during the fourth scan when the sample is not present. This process is repeated at a plurality of scan points sufficient to produce a video image of a microstructural property, such as porosity, of the material. After the scanning is completed, the digitized waveforms are retrieved from the computer and the time delay between the first two successive echoes received from the back surface of the material at each scan point is determined. The time delay between the two different reflections or echoes received off the reflector (with and without the transmitted wave going through the sample) is also determined for each scan point. The wave velocity at each scan point is then calculated from the time delays and the speed of the transmitted wave in the liquid. The velocity values for all of the scan points are scaled to corresponding proportional color or grey scale values which are then displayed on a video screen or cathode ray tube (CRT). Thus, in this embodiment of the invention, four separate scans are made at each scan point to separately receive, as analog waveforms, the first two successive ultrasonic echoes off the back surface of the sample and the first echo off the front surface of the reflector both with and without going through said sample; digitizing and storing the waveforms; retrieving the digitized waveforms; determining the received time delay between the first two successive sample back surface echoes and between the two reflector front surface echoes; calculating the wave velocity at each scan point; scaling the calculated velocities to corresponding proportional color or gray scale values, and displaying the resulting image. The wave velocity at each scan point is calculated from

$$v=c\left(\frac{\Delta t}{2\tau}+1\right)$$

wherein 2τ is the received time delay between the two successive sample back surface echoes, wherein Δt is the time delay between the two different echoes received from the reflector with and without going through the sample, and wherein c is the speed of the transmitted ultrasound wave in the liquid. The embodiment in which three separate scans are made is similar to that in which four separate scans are made, with the difference being that during the first scan the first two succesive reflections or echoes off the back surface of the sample are received, digitized and stored. It will be noted that above equation does not include the sample thickness value. This means that the thickness of the sample need not be measured or known.

As set forth above, prior to the two, three or four scans during which the sample is evaluated, nonlevelness and sample thickness variations are accounted for and eliminated by pre-scans to insure that the received reflections or echoes are within their set time windows to provide a complete waveform for evaluation and cross-correlation to accurately obtain the time delay data used in calculating the velocity values. In the case of a sample having a thickness variation in the form of a uniform thickness variation from one edge to another, preliminary scans are performed along a single line in both the the x- and y- directions of the sample to provide slant correction factors. The slant correction factors are input into the computer scan parameter file so these variations are taken into account during the automatic scanning for the material evaluation.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 schematically illustrates the spatial relationship between the transducer, liquid, material sample, reflector plate and the transmitted and directions. Similarly, liquid 12 is connected to means not shown for maintaining the temperature of the liquid preferably within at least about ± 1^0F of the temperature at which the scans are to be run. It is possible to maintain the liquid temperature within ± 0.1^0F. The better the temperature control, the more accurate the results will be. For example, if the temperature of the immersion liquid is ± 1^0F and the liquid is water, a 1.5% error in velocity is possible. If the porosity fraction or other property of the material at a particular point is such as to result in a velocity value difference in the sample of 2%, only a 0.5% microstructural velocity difference might be detected if a ± 1^0F temperature variation is present during the scan. At each scan point an ultrasonic wave 22 of a known frequency is transmitted from transducer 10 through liquid 12 and into material sample 14. Entering material 14 causes part of wave 22 to be reflected (not shown) off the top surface of the sample, with the rest of the wave passing through the material as 23. Part of wave 23 continues through the material and to the top surface of accoustic reflector 16 as 24, is reflected back off the top surface of reflector 16 as 25, passes back through the sample 14 and returns to the transducer 10 as wave 26. A portion of wave 23 is reflected off the back surface of the sample and returns to the transducer as 27. Part of the wave 23 reflected off the back surface of the material is reflected off the top surface, returns to the back surface, is again reflected back to the top surface and exits as wave 28. Waves 27 and 28 are the first two successive back surface reflected waves used in the method of the invention at each scan point. Not shown is the wave transmitted through the liquid and reflected back to the transducer without going through the material. This wave which is not shown and wave 26 are the two reflector front surface echoes used in the method of the invention. Motorized stages 19 and 20 form part of an automated scanning system which incrementally moves in both the x- and y- directions to obtain an ordered array of points across the entire surface of the material sample. A 20 MHz, broadband transducer was used in the practice of the invention. Broadband transducers emit a broadband frequency content dominated by a center frequency. That is, they are made to emit at a nominal frequency proximate that of the design frequency (e.g., 20 MHz), with a Gaussian fall-off on either side of the nominal center frequency. Thus, a 20 MHz broadband transducer will also emit frequencies slightly above and below the nominal center frequency of 20 MHz. In the Piche article referred to above, although the two different reflector front surface echoes are captured and recorded, the first front surface echo and the first back surface echo are captured and recorded. This is different from the method of the invention which captures and records the first two successive sample back surface echoes and not the first front sample surface echo. Further, Piche does not use automatic sample scanning or digital imaging.

Figures 2(a) and 2(b) graphically illustrate the reflected waveforms received and displayed on the CRT of an oscilloscope as time domain analog waveforms. Turning to Figures 2(a) and 2(b), the intensity or strength of the received waveform is displayed as voltage amplitude, which is the ordinate of the graph, and the received time delay as the abscissa. In this representation, B1, B2 and M' refer to waves 27, 28 and 26 of Figure 1, respectively, with M" representing the wave transmitted through the liquid and reflected off the front surface of the reflector without passing through the material sample. The time delay between the first two successive echoes reflected from the back or bottom surface of the material back to the transducer, B1 and B2, is readily obtained, as is the time delay between the two reflections received from the front surface of the reflector, M' and M". Since the velocity of the ultrasonic wave is faster in denser media than in less dense media, voids, delaminations, porosity and other density variables within the material are obtained as a function of the speed of the wave, which is determined by the time delay between the first two successive echoes received which have been reflected off the back of the material, and the time delay between the two different reflections from the front surface of the reflector. As set forth above under SUMMARY, the speed or velocity of the transmitted wave traveling through the material sample is determined according to the simple equation:

$$v=c\left(\frac{\Delta t}{2\tau}+1\right)$$

wherein 2τ is the received time delay between the two successive material sample back surface echoes, wherein Δt is the time delay between the two different echoes received from the reflector with and without going through said sample, and wherein c is the speed of the transmitted wave in the liquid. This equation is accurate for a single point measurement. Prior art ultrasonic velocity scan techniques such as that of Roth et. al. in the quantitative mapping publication referred to above, assume that the material sample is of uniform thickness and do not take into account nonlevelness and material thickness variations as does the method of the invention.

In the practice of the method of the invention, tank 18 may be made of any suitable material. Clear plastic such as polymethylmethacrylate (e.g., Lucite or Plexoglass) has been found useful. The sample tank contains a suitable elastic liquid, such as water, as the immersion fluid to provide an accoustic coupling between the transducer, material and reflector plate. Since the x-, y- direction scans made across the sample surface in the method of the invention can take a significant amount of time compared to that for a single point measurement and since the speed of sound in a liquid is also a function of temperature, the water is maintained at a constant temperature during the scanning. This is readily accomplished simply by using a constant temperature regulating means, such as a constant temperature water circulator, for maintaining the desired temperature constant during the ultrasonic scanning. It is convenient to keep the temperature of the water at about ambient or $68^0F \pm 1^0F$ during the scan, although other temperatures may be used if desired, as long as the temperature is maintained within no more than $\pm 1^0F$. In the case of distilled, deionized water, the wave velocity may be obtained from published tables. However, tap water may be used as long as the velocity in the water is actually measured. The reflector is placed on the bottom of the tank. Other immersion liquids may be used, if desired, such as Dow Corning 704 vacuum pump oil.

The reflector is a solid plate of material having an accoustic impedance significantly different from that of the liquid or water. A flat plate of tungsten (e.g., 1/16"-1/8" thick) is preferably used, because tungsten has an accoustic impedance almost two orders of magnitude higher than water in units of g/cm^2-sec. The use of a tungsten plate results in the highest possible reflection amplitude of any solid material for the echoes reflecting off the front surface of the reflector plate. This large difference in accoustic impedance is important when attempting to obtain ultrasonic echoes that have to travel into and through immersion liquid and the sample, bounce off the reflector plate, and travel back through the liquid and sample to the the transducer for reception. High frequency ultrasound provides greater time resolution than lower frequencies and is therefore more desireable for greater accuracy of the velocity of the ultrasound through the sample and corresponding velocity image. The higher the frequency, the greater the velocity accuracy. By having the highest reflection amplitude possible, it is possible to use the method of the invention (a) at higher frequencies where attenuation through the sample is greater that if using lower frequencies and (b) with materials that significantly attenuate ultrasound, such as composite materials. By high frequency ultrasound is meant from 1-100 MHz, typically 3-50 MHz and more typically 10-30 MHz.

The material sample is easily positioned over the reflector plate by using spacers on top of the plate and placing the material on top of the spacers. It is important that the spacers have the same height or thickness so that the material is as level as possible. Lucite is available as sheets which are very uniformly thick and it is convenient to use 0.5" cubes of this plastic as spacers. The material sample, such as a plate of silicon nitride ceramic, is placed on the plastic spacers over the tungsten reflector plate prior to scanning.

Figure 4 schematically illustrates, in block diagram fashion, the basic system and instrumentation used for the scanning and ultrasonic imaging according to an embodiment used in the practice of the invention.

Thus, referring to Figure 4, the basic instrumentation includes a transducer 50, a pulser-receiver 52, and a programmable waveform digitizer 54 having associated with it a vertical voltage amplifier 56, programmable time base 58, and anolog and digital monitors 60 and 62, respectively. Also included are a time delay or synthesizer 64, an image processor 66, an X, Y, Z controller 68, computer or central processing unit (CPU) 70, and video display 72. In the embodiment shown, the computer 70 is a CPU with terminal 74 and associated video display 76 also forming part of the system. Monitors 60 and 62, along with digitizer 54, voltage amplifier 56 and time base 58 also serve as respective analog and digital oscilloscopes. The time synthesizer, time base, voltage amplifier and waveform digitizer are all general purpose interface [IEEE- 488] bus (hereinafter "GPIB") programmable and interconnected via GPIB cables. The computer 70 is programmed in Fortran and contains an image processor system which is connected to the video color and gray scale display 72. The computer controls the GPIB instrumentation and acquiring of the desired waveforms via the GPIB. The process includes data acquisition, analysis/calculation, image processing and display. The Fortran software, with callable routines in in IEX-VMS interface software to communicate with the GPIB instruments is written for instrument control and waveform acquisition following the method of Generazio, et. al. in *Interfacing Laboratory Instruments to Multiuser Virtual Memory Computers*, NASA Technical Memorandum

4106 (1985), the disclosure of which is incorporated herein by reference. The Fortran programs used in the practice of the invention including the scanning program, the analysis and cross-correlation program, the grey scale imagemaker program, and the display program are contained in the attached Appendix. The wave form digitizer is a Tektronics 7912 AD Programmable Digitizer along with a Tektronics 7A16 P Programmable Vertical Voltage Amplifier (voltage base) and a Tektronics 7B90 P Programmable Time Base. The time delay (time synthesizer) is a Hewlett Packard Model 5359A and the X, Y, Z programmable stepper motor controller and associated tables is a Klinger Scientific C-1.22. The ultrasomic pulser-receiver is a Panametrics Model 5601 and the transducer used in the scanning of the silicon nitride ceramic disk in the example below is a Panametrics 20 MHz, longitudinal, unfocused, broad band transducer. The computer is a Digital Equipment model Microvax II.

In the practice of the invention, the image processer is a Grinnell Systems Grinnell 274 Image Processing System and the Grinnell Systems GMR Series Software Package, Release 2.2, June 19,1981, available from McLoud Associates, 165-F Croftich Lane, Campbell, CA 95008, the disclosure of which is also incorporated herein by reference. Two video displays are used, one of which is a DEC VT340 terminal, which is the user terminal attached to the computer, and a Mitsubishi 20LP is the video dsplay monitor attached to the image processing system. High level VAX Fortran software used for driving the system is included in the Appendix as set forth above. The Grinnell library of Fortran subroutines is called from this high level software. The video display shows ultrasonic images.

The pulser-receiver applies the voltage pulse to the transducer to generate the ultrasonic waves into the sample and to the reflector plate and also receives the raw ultrasonic echo waveforms from the transducer. The approximate times where the echo waveforms are expected to occur are determined a priori (prior to the automatic scanning for the material evaluation) using the time systhesizer to find and position the echo waveforms on the oscilloscope. The time base and voltage amplifier are used to modify the time and voltage scales to view the waveforms on the oscilloscope. Both the time base and the time synthesizer are externally triggered by the pulser-receiver (a +2 volt synchronizing pulse). Triggering occurs on the positive slope of the pulse. The time base is adjustable over the range of from 1 psec - 500 msec/div on the oscilloscope, with the optimum setting for each waveform determined a priori and input to a data file in the computer. The pulser-receiver output is connected to the voltage amplifier. The voltage amplifier, selectable over the range 50 mV - 1 V/div, is automatically adjusted by the digitizer so that the entire received analog waveform is digitized with maximum amplitude fit onto the digital waveform monitor. The digitizer digitizes each waveform received into 512 point arrays (at a sampling rate ranging from 0.512

- 1.024 GHz depending on the time base time/division setting). Each waveform is acquired 64 times and averaged to obtain a smoother waveform with averaged noise levels using a Fortran algorithm included in the scanning program in the Appendix and which is also found in the NASA Technical Memorandum 4106 referred to above. The X and Y positional and Z intensity outputs from the waveform digitizer are attached to the analog and digital monitors 60 and 62. The analog monitor is used for the prescans and the digital for the automatic scanning.

As set forth under the SUMMARY, prior to the two, three or four scans during which the sample is evaluated, nonlevelness and sample thickness variations are accounted for and eliminated by pre-scans to insure that the received reflections or echoes are within their set time windows to provide a complete waveform for evaluation and cross-correlation to accurately obtain the time delay data used in calculating the velocity values. That is, during the nonlevelness and material thickness variation scans, the operator notes if the time delay of each echo received at each scan point is such that it is no longer centered within the oscilloscope time window. If a received echo is not centered within the time window on the scope, this is noted and the time window changed for each such echo received until the received echo time domain waveform is completely within the new time window set for it to insure that the complete time domain waveform is captured or gated completely within the new window. This time delay information at each scan point is inputed into the scan parameter file and recalled during the actual scanning during the material evaluation, to automatically adjust the time delay for the received echoes at each scan point so that each echo received during the scanning is centered within the time window set for it. This is very time consuming to do for each scan point. However, in the case of a sample having a thickness variation in the form of a uniform thickness variation from one edge to another, preliminary scans are performed along a single line in both the the x- and y- directions of the sample to provide slant correction factors. The slant correction factors are input into the computer scan parameter file so these variations are taken into account during the automatic scanning for the material evaluation. It is important that the echo at each scan point is centered in its time window, because the whole pulse or echo time domain waveform is needed to give the precise time delay between echoes for the cross-correlation which provides the velocity value. In doing this for a wedge shaped sample, prior to the automatic scan, the transducer scans along two straight lines over the sample, once in the the x- direction and once in the y- direction, during which an operator notes the echo received from the first and last scan points, starting from the first scan point which is generally at one corner of the area defined for scanning. The time difference from the sample end-to-end in each of the x- and y- directions of the first and last scan point is noted by the operator who then adjusts the time base for each echo if needed to insure that it is centered within the time frame set for it. This is done so that so that each echo received during the scans in which the material is being evaluated is centered (gated) within the oscilloscope time window set for it so that the received waveform is displayed with the maximum possible amplitude on the CRT and still have the complete waveform. This permits the maximum time resolution of individual echoes without losing any part of the time domain waveform which appears on the CRT screen as a function of voltage (amplitude) and time, wherein time is the x- axis and voltage or amplitude is the y- axis. It is important and forms an aspect of the invention that the complete waveform or pulse echo be captured or "gated" on the CRT screen in order to perform an accurate cross-correlation later on in the procedure of the process of the invention. The cross-correlation of echoes provides the precise time delay between received echoes or pulses which is required to calculate the velocity or speed of the ultrasound in the material evaluated which, in turn, provides the information to gray or color scale the velocity data into a digitized map of the material density. This slant correction procedure also allows an accurate evaluation to be made without the need for specialized leveling equipment. These x- and y- direction time window corrections are called slant correction factors and they are inputted into the scan parameter file in units of "nsec/μm" where (a) the number of nsec is the time extent from sample end-to-end that is required to keep the specific echo centered and is determined using the (a) time synthesizer to reposition echoes in time and (b) the number of μm is the distance traveled by the transducer for which this slant factor is determined. By way of an illustrative, but nonlimiting example, the first scan point (0,0) along the x- direction may have a B1 echo centered at a time = 6.77 μsec, while the last scan point (40,0), may have B1 centered at time = 7.14 μsec. If the x- direction scan line length is 40 mm, the x-direction slant correction factor is obtained from (7.14 - 6.77)/40 μsec/mm. It should be noted that slant correction factors can be negative as well as positive numbers. The location of the time window during scanning for the material evaluation is automatically adjusted via computer control by using the formula:

$$W_{DT} = T_I + [(X_{SC})(X_{SN})(X_{SI}) + (Y_{SC})(Y_{SN})(Y_{SI})]$$

wherein W_{DT} is the correct delay time window at a particular scan location, T_I is the time delay at the the initial scan location, X_{SC} and Y_{SC} are the x- and y- direction slant correction factors, X_{SN} and Y_{SN} are the scan point numbers in the x- and y- directions, and X_{SI} and Y_{SI} are the x- and y- direction scan increments. With many samples it has been found that the slant correction factors turn out to be the same for the B1 ,B2 echoes and the slant correction factors for the M',M" echoes are the same. However, for some samples (e.g., thick samples), they may not be the same. In such cases a first x- and y-direction scan is made for the B1 echoes and a second x- and y- direction scan made for the B2 echoes. The same holds for the M' and M" echoes for which two separate scans are made in the x- and y- directions.

A scan parameter file is input into a computer which contains all of the information necessary to automatically scan the material sample being evaluated. This information includes a predefined and ordered array of scan points over which to run the scan. By way of an illustrative, but nonlimiting example, in an example of the method of the invention in which the material being evaluated was a monolithic ceramic wedge, the scan consisted of a 41 (X-direction) by 81 (y-direction) grid of measurements for a total of 3,200 scan points, with each measurement or scan point separated by 1 mm (x- and y- scan increment). Information input into the scan parameter file (NOTHICK_ALLSHAPE1.DAT) includes the following:

```
C **TITLE** NOTHICK ALLSHAPE1.DAT
C ** SCAN INCREMENT (uM) IN X-DIRECTION IS:
1000.
C ** SCAN INCREMENT (uM) IN Y-DIRECTION IS:
1000.
C ** SCAN LENGTH (uM) IN X-DIRECTION IS:
40000.
```

C ** SCAN LENGTH (uM) IN Y-DIRECTION IS:

80000.

C ** X-DIRECTION SLANT CORRECTION FACTOR (nsec/uM) FOR B1 & B2 ECHOES IS:

-0.0055

C ** X-DIRECTION SLANT CORRECTION FACTOR (nsec/uM) FOR REFLECTOR ECHOES IS:

-0.0055

C ** Y-DIRECTION SLANT CORRECTION FACTOR (nsec/uM) FOR B1 & B2 ECHOES IS:

-0.00175

C ** Y-DIRECTION SLANT CORRECTION FACTOR (nsec/uM) FOR REFLECTOR ECHOES IS

0.0

C ** TIME LOCATION (uSEC) OF B1 ECHO AT SCAN ORIGIN IS:

52.83

C ** TIME LOCATION (uSEC) OF B2 ECHO AT SCAN ORIGIN IS:

52.31

C ** TIME LOCATION (uSEC) OF REFLECTOR ECHO W/SAMPLE PRESENT AT SCAN LOCATION IS:

69.46

C ** TIME LOCATION (uSEC) OF REFLECTOR ECHO W/O SAMPLE PRESENT AT SCAN LOCATION IS:

72.48

C ** IMMERSION FLUID VELOCITY (cm/uSEC) IS:

0.148

C ** B2 PHASE-INVERTED WRT B1 (Y/N)?:

N

C ** M" PHASE INVERTED WRT M' (Y/N)?:

N

As set forth above, in the method of the invention, the transducer is activated so that the first front surface echo off the sample, the first two successive back surface echoes, and the first echo off the reflector plate are all seen in the oscilloscope display at the same time by adjusting the the time base to the appropriate time per division setting and adjusting the time synthesizer delay time. Viewing the first front surface echo off the sample enables the operator to know if the back surface echoes are also on the CRT screen. The unfocused transducer is positioned above the sample at a distance determined initially by the natural focal distance. When using an unfocused transducer a good initial starting height is approximately one to two inches above the sample. The reflector plate front surface echo may be low in amplitude compared to the sample back surface echoes, so that the the pulser-receiver gain/attenuation or vertical amplifier gain settings may have to be increased to see this echo. It is important not to confuse the echoes off the front surface of the reflector plate with the second set of echoes originating from the front and back surfaces of the sample. The second set of echoes originating from the front and back surface of the sample will always occur at twice the delay time where the first set of these echoes appears. For example, if the first set of echoes begins at 50 msec on the digital oscilloscope, the second set will begin at 100 msec. If using, for example, a three milimeter thick sample placed on 0.5" thick plastic supports on the reflector plate, the first reflector echo will occur at about 20 msec after the time where the first set of echoes originates and thus the reflector echo will be seen at about 70 msec in this illustration. Another way to note the reflector plate echo is to raise and lower the sample while noting the location of the stationary echo corresponding to the stationary reflector plate. It is essential to have reflector plate echoes that will not interfere with the second set of echoes originating from the front and back sample surfaces.

Attention is next focused on the first back surface echo from the sample, B1. The echo is centered in the oscilloscope time window to obtaining maximum time resolution by adjusting the time base time per division and the time synthesizer delay. The synthesizer time is recorded and inputted into the scan parameter computer file. This procedure is repeated for the second back surface sample echo, B2, the first front surface echo off the reflector plate with the sample present, M' and the first echo off the reflector plate with the sample removed, M". The next step is to account for and eliminate any nonlevelness in the set-up and also sample thickness variations. This done at each scan point, except that in the case of uniform thickness variations in the sample, the slant correction factors outlined above are determined and input into the scan parameter file in the computer.

The scanning is then automatically performed through the remainder of the scanning points previously inputted into the scan parameter file in the computer using a program written in Fortran and IEX GPIB to perform the scanning and also to obtain maximum vertical voltage resolution of the received ultrasonic waveforms. Scanning is accomplished through the use of computer controlled x-, and y- microscanning tables used to reposition the sample in the x- or y- direction in a 1 mm increment (other increments may be used at the convenience and discretion of the practitioner) for the next measurement. The ultrasonic waveforms received are then digitized (512 x 512 pixel resolution) at each scan location and stored successively in the scan data file in the computer. Four separate ultrasonic scans are performed at each scan location. As set forth above, the echoes are B1 (first echo off sample back surface, obtained in first scan), B2 (second echo off sample back surface, obtained in second scan), M' (first echo off front surface of reflector plate with the sample present, obtained in third scan), and M" (first echo off front surface of reflector plate without the sample present, obtained in fourth scan). Each of the four echoes is obtained in a separate scan to obtain the maximum time resolution for each echo by setting, before each scan during the nonlevelness and material thickness variation procedure, the optimum time per division setting on the oscilloscope time base that allows maximum time resolution. The minimum number of scans for this thickness-elimination procedure is two, but the time per division setting for only two scans cannot be obtained in this case as the time per division setting would be fixed for all three echoes obtained in the first of the scans using this scan procedure.

The following is an algorithm of a scanning program which accounts for and eliminates the nonlevelness of the set-up and uniform thickness variation effects of the sample in the resulting ultrasonic image displayed on the video, the code for which is included in the Appendix.

1) Determine the scan lengths and scan increments in the x- and y- directions, time positions of echoes at scan origin, slant correction factors, and immersion fluid velocity.

2) Edit NOTHICK_ALLSHAPE1.DAT FILE, which is the scan parameter file, and input information from 1) above.

3) Start scanner fortran program on computer which automatically does the following:

A) Initialize all GPIB instrumentation, which includes the time synthesizer, digitizer, time base, voltage amplifier, Klinger X, Y stages.

B) Perform scan to digitize B1 echoes and store in file .

I) Digitize B1 at scan origin

Adjust voltage base for echo with maximum amplitude in video/oscilloscope window

.Move Klinger tables under transducer in x- direction specified x- direction increment

Time synthesizer moves to delay time position determined by B1, B2, slant correction factors. This results in echo in video being centered in the Tektronics analog video/oscilloscope display and subsequently digitized and stored.

--Time position $= T_0 + [(S_X)(N_X)(I_X) + (S_Y)(N_Y)(I_Y)]$

where T_0 = correct delay time window at a particular scan location S_X = x- direction slant correction factor (nsec/μm)

N_X = scan point number in x- direction

I_X = x- direction scan increment (μm)

S_Y = y- direction slant correction factor (nsec/μm)

N_Y = scan point number in y- direction

I_Y = y- direction scan increment (μm)

II) Repeat I) until one scan line in x- direction is completed.

III) Increment transducer in y- direction specified y- direction increment and repeat I)-II).

IV) Repeat I)-III) until y- scan length is traversed and scan is completed.

V) Return Klinger tables to scan origin.

C) Perform scan to digitize B2 echoes and store in file by repeating steps B(I-V)

D) Perform scan to digitize reflector echoes with sample present and store in file by repeating steps B(I-V), but using reflector echo slant correction factor

E) Remove sample. Perform scan to digitize reflector echoes without sample present and store in file by repeating steps B(I-V), but using reflector echo slant correction factor

4) Start velocity calculation Fortran program on computer to produce a file of velocities at each scan location by performing the cross-correlation algorithm.

5) Start image formation Fortran program on computer which results in a file of values between 0 and 255 which scale directly with the velocity values.

6) Start image display program which brings grey scale level image up on video.

Before initiating the scanning procedure, the temperature of the water or other immersion fluid is measured. If the fluid is water, published tables or graphs of temperature and velocity can be used to determine the velocity of the ultrasound in the constant temperature water bath. If the immersion liquid is a liquid other than water, or if a more precise temperature than that available in published graphs and tables is desired, the velocity of the ultrasound in the liquid is determined by recording the times (T_P) where ultrasonic peaks occur for two different vertical positions (Z1 and Z2) of the transducer above the reflector plate. The velocity, V, is then determined from

$$V = (Z1 - Z2)/(T_P1 - T_P2)$$

The phase relationships of (a) B1 compared to B2 and also (2) the reflector front surface echo with the sample present (M') compared to that without the sample present (M") are examined. These phase relationships are important for the computation of the velocity image of the scanned sample. The quantity 2τ is obtained by cross-correlating echoes B1 and B2 which is defined as the precise time delay between the B1 and B2 echoes. If B1 and B2 are phase inverted with respect to each other, the time occurrence of the minimum in the cross-correlation function is used to obtain 2τ. If M' and M" are phase inverted with respect to each other, the time occurrence of the minimum in the cross-correlation function is used to obtain Δt. Otherwise, at the time occurence of the maximum in the cross-correlation function is used. Figures 3(a) and 3(b) graphically illustrate the case in which B2 is phase inverted with respect to B1. The same holds for M' and M". Phase relationships generally remain the same throughout the scan, unless significant discrete microstructural defects are encountered by the ultrasonic wave.

After the scan has been completed and all the received echoes have been digitized and stored in the scan data file in the computer, they are recalled from the data file to perform the velocity image calculation for each scan location. In performing this cross-correlation, an overlap method is used by the computer based on a cross-correlation program using Fast Fourier Trasnforms published in pages 415 and 416 (Correlation and Autocorrolation Using the FFT) in the book *Numerical Recipes - The Art of Scientific Computing*, by Press, et. al., 1988 Edition, Cambridge Univ. Press.. The Fortran program used is in the Appendix. Echoes M' and M" are also cross-correlated to obtain Δt where where M' is the echo reflected off the reflector plate front surface with the sample present, M" is the echo reflected off the reflector plate front surface without the sample present, and Δt is the time delay between them. If M' and M" are phase inverted with respect to each other, the time occurrence of the minimum in the cross-correlation function is used to obtain Δt. Otherwise the time occurence of the maximum in the cross-correlation function is used. The velocity, V, at each scan location is then calculated from the equation referred to above. The velocity value for each scan location is sequentially stored in the computer. After the scan is completed the velocity values are scaled on a gray or color scale with a value directly proportional to the velocity values, with the highest and lowest scale values corresponding to the highest and lowest velocity values.

The invention will be further understood with reference to the example below.

Example

In this example, a sample of silicon nitride ceramic was evaluated using the thickness based velocity image method disclosed in the NASA Technical Memorandum TP 3377 referred to under Background. This method is based on a velocity, cross-correlation ultrasonic imaging method without the pre-scan to account for and eliminate nonlevelness in the set-up and sample thickness variations. In this method, only the first two sample back surface echoes are captured and evaluated. The silicon nitride ceramic was 3.5 mm thick with a uniform 300 micron thickness gradient. Very coarse time scaling was used so that the B1 and B2 echoes stayed in the time window while the sample thickness changed as the scan proceeded.

The same silicon nitride ceramic sample was also scanned and velocity imaged on a grey scale according to the method of the invention which included the prescans to eliminate set-up and sample thickness variations and which also captured and cross-corrolated both the first two successive sample back surface echoes and the two different reflector front surface echoes.

In both cases, the 20 MHz broad band transducer was uses, the immersion liquid was water and the back plate was tungsten as set forth above.

Figures 5(a) and 5(b) are photographs of video grey scale displays of the thickness based ultrasonic velocity image of a ceramic according to the prior art method, and an image according to the method of the invention which included the prescans, respectively. Referring to Figure 5(a), it is seen that the top defect is masked due to that part of the sample being thicker than the bottom part. Also, the defect near the bottom is not too discernable and the lower portion is very light due to it being thinner. In marked contrast and as shown in Figure 5(b), the method of the invention clearly and correctly illustrates the defect areas, including resolution of the upper defect and an overall porosity gradient in the sample. It is believed that this demonstrates the efficacy and improvement to the art of the invention.

It is understood that various other embodiments and modifications in the practice of the invention will be apparent to, and can be readily made by, those skilled in the art without departing from the scope and spirit of the invention described above. Accordingly, it is not intended that the scope of the claims appended hereto be limited to the exact description set forth above, but rather that the claims be construed as encompassing all of the features of patentable novelty which reside in the present invention, including all the features and embodiments which would be treated as equivalents thereof by those skilled in the art to which the invention pertains.

NASA CASE NO. LEW-16,257-1

PULSE-ECHO ULTRASONIC IMAGING METHOD FOR ELIMINATING SAMPLE THICKNESS VARIATION EFFECTS

Abstract of the Disclosure

A pulse-echo, immersion method for ultrasonic evaluation of a material which accounts for and eliminates nonlevelness in the equipment set-up and sample thickness variation effects employs a single transducer, automatic scanning and digital imaging to obtain an image of a property of the material, such as pore fraction. The nonlevelness and thickness variation effects are accounted for by pre-scan adjusments of the time window to insure that the echoes received at each scan point are gated in the center of the window. This information is input into the scan file so that, during the automatic scanning for the material evaluation, each received echo is centered in its time window. A cross-correlation function calculates the velocity at each scan point, which is then proportionalized to a color or grey scale and displayed on a video screen.

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Serial # 08/546 972
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LEW-16,257-1

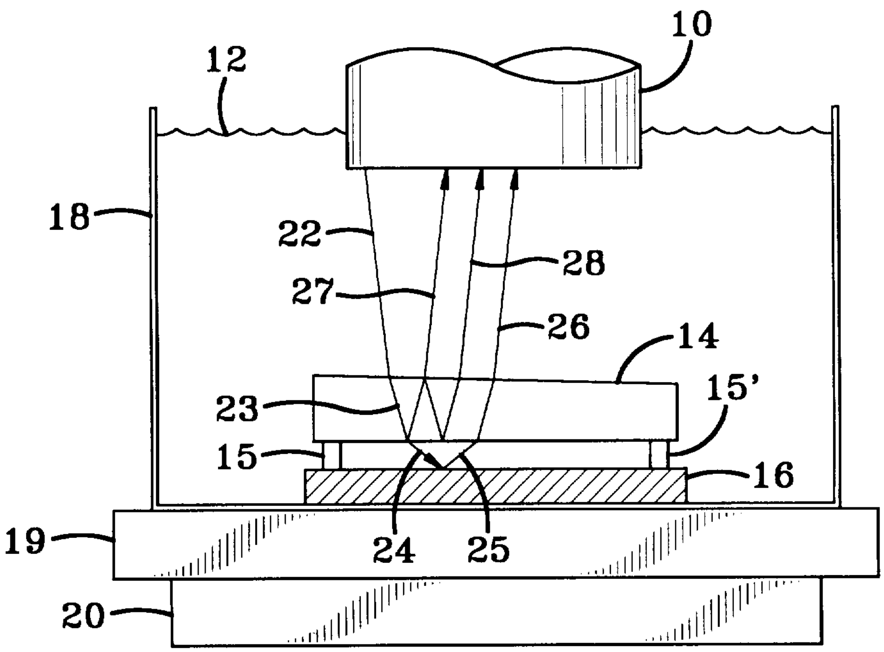


FIG-1

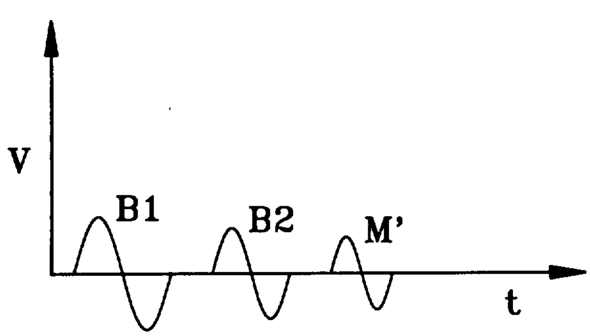


FIG-2A

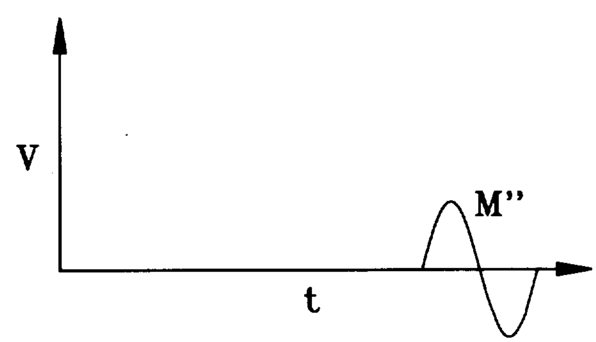
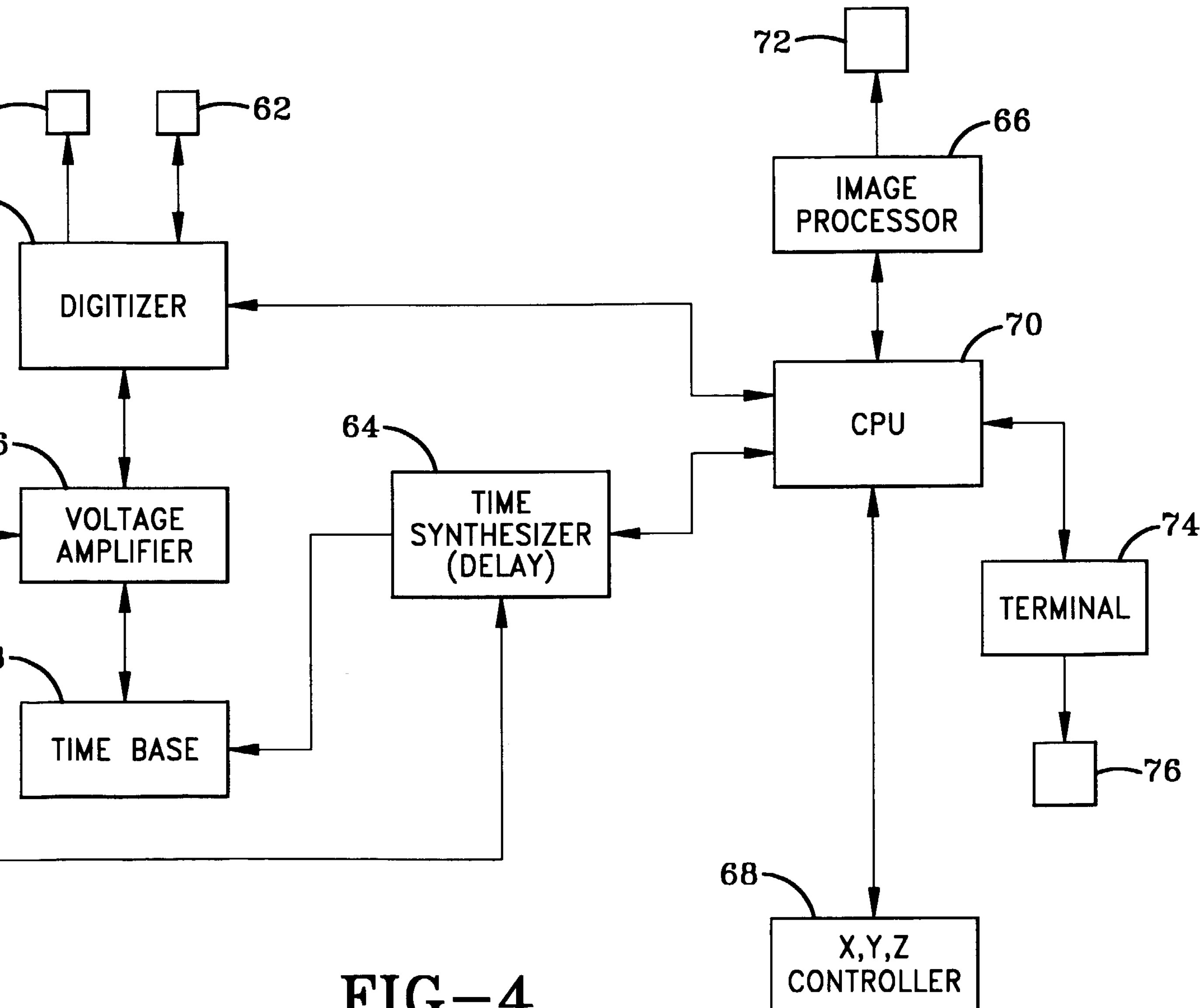


FIG-2B

LEW-16,257-1



FIG—4

LEW-16,257-1

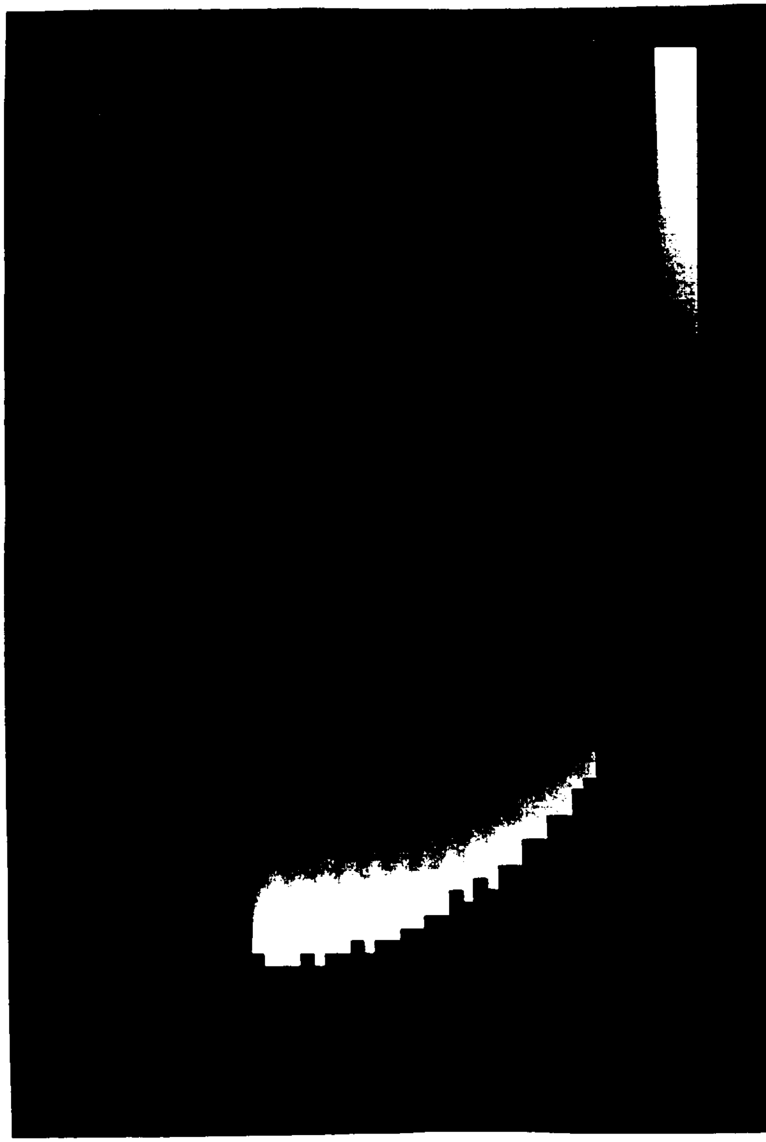
 

FIG-5A FIG-5B